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Measurement of the Polarization in the Decay $B^0 \to J/\psi K^{*0}$ in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

This paper reports on the measurement of the polarization in the decay $B^0 \to J/\psi K^{*0}$ using data collected at the Collider Detector at Fermilab in $\overline{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. B^0 mesons were reconstructed through the decay chain $B^0 \to J/\psi K^{*0}, J/\psi \to \mu^+\mu^-, K^{*0} \to K^+\pi^-$. A sample of 60 ± 11 events was used in the measurement, yielding the result $\Gamma_L/\Gamma = 0.66 \pm 0.10$ (stat) $^{+0.08}_{-0.10}$ (sys).

The pseudoscalar to vector-vector decay $B^0 \to J/\psi K^{*0}$ allows different polarizations in the final state. The measurement of this polarization tests the factorization hypothesis for hadronic decays and also helps determine if the decay is useful for studies of CP violation. The model of Bauer, Stech, and Wirbel [1], which utilizes the factorization approximation, predicts that the amount of longitudinal polarization Γ_L/Γ is 0.57. Using heavy quark effective theory calculations and a measurement of the $D \to K^*$ form factor from FNAL E691 gives $\Gamma_L/\Gamma = 0.73$ [2]. Early results from ARGUS [3] suggest that the decay is completely longitudinally polarized. A recent measurement from CLEO gives the value $\Gamma_L/\Gamma = 0.80 \pm 0.05 \pm 0.08$ [4]. This paper describes a preliminary analysis of this decay performed by the Collider Detector at Fermilab (CDF) collaboration.

Using data collected in 1992–93 at the Fermilab Tevatron, B^0 mesons were reconstructed through the decay chain $B^0 \to J/\psi K^{*0}$, $J/\psi \to \mu^+\mu^-$, $K^{*0} \to K^+\pi^-$ [5]. The data set consisted of approximately 19 pb^{-1} of $\overline{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. The CDF has been described in detail elsewhere [6], and components relevant to this analysis are briefly described here. Proceeding outward from the interaction point the elements of the detector include the Silicon Vertex Detector (SVX) [7], Vertex Time Projection Chamber (VTX), Central Tracking Chamber (CTC), a solenoidal magnet, electromagnetic and hadronic calorimeters, and the muon chambers. The SVX consists of four layers of silicon strip detectors with r-ϕ readout [8]. The SVX extends $\sim \pm 30$ cm in z causing it to have a geometrical acceptance of about 60% since the interactions are distributed along the beam axis with a σ of $\sim$ 30 cm. The r-z tracking information from the VTX is used to determine the primary vertex. The CTC is an 84 layer drift chamber covering $\mid \eta \mid < 1.1$, where $\eta = -ln\,[\tan(\theta/2)]$ is the pseudorapidity. The CTC measures momentum in three dimensions in a 1.4116 T axial magnetic field. The combined CTC/SVX momentum resolution is $\delta P_T/P_T = [(0.0009 P_T)^2 + (0.0066)^2]^{\frac{1}{2}}$ where P_T is the momentum transverse to the beam. The calorimeters serve as absorbers for this analysis. The central muon system consists of three detector elements. The Central Muon Chambers (CMU) are located behind $\sim$ 5 absorption lengths and cover 85% of the azimuthal region for $\mid \eta \mid \leq 0.6$. This η region is further instrumented by the Central Muon Upgrade (CMP) behind a total of $\sim$ 8 absorption lengths. The Central Muon Extension chambers (CMX) are located behind $\sim$ 6 absorption lengths and cover 67% of the azimuthal region for $0.6 < \mid \eta \mid < 1.0$.

The data sample used in this analysis was collected by the dimuon triggers in the CDF three level trigger system. At Level 1 two charged track segments were required in the muon chambers. The trigger efficiency for a muon at Level 1 rose from 50% at $P_T = 1.6$ GeV/c to 90% at $P_T = 3.1$ GeV/c with a plateau of 94%. The segments had to be separated by at least 0.09 radians in ϕ. The Level 2 trigger required that at least one of the muon segments was matched in ϕ to a CTC track found by the Central Fast Tracker (CFT). The efficiency for finding a track in the CFT rose from 50% at $P_T = 2.65$ GeV/c to 90% at $P_T = 3.1$ GeV/c and reached a plateau of 93%. At Level 3 the trigger, using online track reconstruction software, required a pair of oppositely charged muons with an invariant mass between 2.8 and 3.4 GeV/c^2.

In order to isolate the J/ψ signal, and to keep the systematic effects from the trigger under control, additional offline requirements were placed on the muons. The match between the extrapolated CTC track and the segment in the muon chamber was required to be less than 3σ, where σ is the expected multiple scattering error combined in quadrature with the measurement errors. SVX information was added to the CTC tracks when it was available. Both muons were required to have a transverse momentum greater than 2.0 GeV/c, and at least one had to have a transverse momentum greater than 2.8 GeV/c. The invariant mass of the dimuon pair was formed while constraining the muon tracks to come from a common vertex. After all of the above requirements were applied there were approximately 41000

J/ψ candidates remaining, with a signal width of about 20 MeV.

Those dimuon pairs within 80 MeV/c^2 of the world average J/ψ mass were combined with other charged tracks to search for B^0 mesons. K^{*0} candidates were formed by selecting pairs of oppositely charged tracks. Both $K^\pm\pi^\mp$ mass assignments were tried. The assignment closer to the K^{*0} mass was used, and the candidate was kept if the $K\pi$ invariant mass was within 80 MeV/c^2 of the mass of the K^{*0}, which has a natural width of 51 MeV/c^2 [9]. All of the tracks were constrained to come from a common vertex, and the dimuons were mass constrained to the world average J/ψ mass. A combined confidence level, CL(χ^2), was formed from the constrained fit and was required to be greater than 1%. Combinatoric backgrounds were reduced by applying requirements on the proper decay distance $c\tau$ and transverse momentum of the B^0 candidate, and on the transverse momentum of the K^{*0}. The requirements were $c\tau > 100$ μm, $P_{T_B} > 8.0$ GeV/c and $P_{T_{K^{*0}}} > 2.0$ GeV/c. The resulting mass distribution is shown in Figure 1. A binned maximum likelihood fit to a gaussian plus a flat background was used, yielding 63 ± 12 events. Regions where a B decay with a missing pion can contribute were excluded from the fit, indicated by the dashed line.

The decay distribution for $B^0 \to J/\psi K^{*0}$, $J/\psi \to \mu^+\mu^-$, $K^{*0} \to K^+\pi^-$ can be written as (*e.g.* see Ref. [2])

$$\frac{d^2\Gamma}{d\cos\theta_{K^*}d\cos\theta_\psi} \propto \frac{1}{4}\sin^2\theta_{K^*}(1+\cos^2\theta_\psi)(\mid H_{+1}\mid^2 + \mid H_{-1}\mid^2) + \cos^2\theta_{K^*}\sin^2\theta_\psi \mid H_0\mid^2$$

where the helicity angle θ_{K^*} is the decay angle of the kaon in the K^{*0} rest frame with respect to the K^{*0} direction in the B rest frame. Similarly, θ_ψ is the decay angle of the muon in the J/ψ rest frame with respect to the J/ψ direction in the B rest frame. The amount of transverse and longitudinal polarization can be written in terms of the helicity amplitudes as

$$\frac{\Gamma_T}{\Gamma} = \frac{\mid H_{+1}\mid^2 + \mid H_{-1}\mid^2}{\mid H_{+1}\mid^2 + \mid H_{-1}\mid^2 + \mid H_0\mid^2}$$

$$\frac{\Gamma_L}{\Gamma} = \frac{\mid H_0\mid^2}{\mid H_{+1}\mid^2 + \mid H_{-1}\mid^2 + \mid H_0\mid^2}.$$

The above expression for the decay distribution has been integrated over the angle ϕ between the decay planes. Integrating separately over θ_{K^*} and θ_ψ gives the relations

$$\frac{d\Gamma}{d\cos\theta_{K^*}} \propto \frac{1}{2} - \alpha\left(-\frac{1}{2} + \cos^2\theta_{K^*}\right) \qquad (1)$$

$$\frac{d\Gamma}{d\cos\theta_\psi} \propto 1 + \alpha\cos^2\theta_\psi \tag{2}$$

where

$$\alpha = \frac{1 - 3\Gamma_L/\Gamma}{1 + \Gamma_L/\Gamma}.$$

For the helicity angle analysis the signal region was defined as $\mid m_{\mu\mu K\pi} - m_B \mid < 0.03$ GeV/c^2 and the sideband regions as $5.15 < m_{\mu\mu K\pi} < 5.237$ GeV/c^2 and $5.327 < m_{\mu\mu K\pi} < 5.41$ GeV/c^2. An unbinned likelihood fit to the helicity distribution was performed. The information from both the K^{*0} and the J/ψ was used by forming an event by event product of likelihoods

$$L = \prod_{i=1}^{n} L_{K_i^*} L_{\psi_i}$$

where $L_{K_i^*}$ and L_{ψ_i} are the likelihood functions. The main components of these functions are the signal shapes in equations 1 and 2, the acceptance functions and the background shapes.

The acceptance curves as a function of θ_{K^*} and θ_ψ were derived from Monte Carlo. The b quark P_T and η distributions were generated according to a next to leading order calculation [10] using MRSD0 structure functions with $\Lambda_4 = 215$ MeV and $\mu = \mu_0 = \sqrt{m_b^2 + {P_T}^2}$. The quarks were fragmented using the Peterson prescription with $\epsilon = 0.006$ [11], and the B^0 meson decay distribution was assumed to be unpolarized. The decay products were processed by a standard CDF detector simulation. The acceptance curves were parameterized with polynomial fits.

The shape of the background as a function of the helicity angles was studied using events in the sidebands of the B^0 mass distribution. In order to increase the number of events in the sideband regions, certain reconstruction requirements were removed. Without the $c\tau$ cut the background distributions appeared to be unpolarized. When the CL(χ^2) cut was removed instead, a similar distribution was obtained. Since the helicity angle distributions are expected to be independent of both the $c\tau$ and CL(χ^2) requirements, the background shape was assumed to be unpolarized. These other two background shapes were used as systematic checks.

The result of the unbinned likelihood fit is $\Gamma_L/\Gamma = 0.66 \pm 0.10$ (stat). The fit is projected onto background subtracted, acceptance corrected, data plots in Figures 2 and 3. The efficacy of this method was tested using the decay $B^+ \to J/\psi K^+$. Fitting the helicity angle

Variation	$\Delta\Gamma_L/\Gamma$
Trigger Model	+0.01 −0.02
Acceptance Curve	+0.04 −0.05
Input Polarization	+0.05 −0.02
Peterson Fragmentation	+0.03
Input P_T Spectrum	+0.02 −0.01
Background Shape	−0.08
Signal Fraction	+0.04
TOTAL	+0.08 −0.10

Table 1: Systematic errors.

distribution for the J/ψ ($L_{K_i^*} = 1$) in the same manner as was used for the B^0 case gives $\Gamma_L/\Gamma = 1.07 \pm 0.07$ (stat), where $\Gamma_L/\Gamma = 1$ is expected.

The systematic studies completed so far are shown in Table 1 and described below. The trigger model systematics were estimated by varying the measured efficiency curves. The uncertainty associated with the determination of the acceptance curve was determined by varying the choice of the functional form for the fit, and accounting for the limited Monte Carlo statistics. The assumed input polarization gives rise to a systematic error since the two one-dimensional acceptance curves were determined separately. The uncertainty was determined by varying the input polarization. Additional systematic errors were determined by varying the Peterson fragmentation model ϵ by ± 0.002 and the b quark input P_T spectrum. To estimate the systematic error associated with the background shape determination the curves obtained from the sidebands were used. Finally, the systematic error associated with the assumed signal to background ratio was determined by allowing the fraction to float in the likelihood fit instead of being fixed from the mass plot.

The polarization result for $B^0 \rightarrow J/\psi K^{*0}$ is $\Gamma_L/\Gamma = 0.66 \pm 0.10$ (stat) $^{+0.08}_{-0.10}$ (sys). The information from both the K^{*0} and the J/ψ were used by taking an event by event product of likelihoods. This preliminary result is in good agreement with the recent CLEO measurement. Although not fully polarized, this decay mode still appears to be useful for CP violation studies at B factories. This result also demonstrates the feasibility of studying the dynamics of B meson decays in a hadron collider environment.

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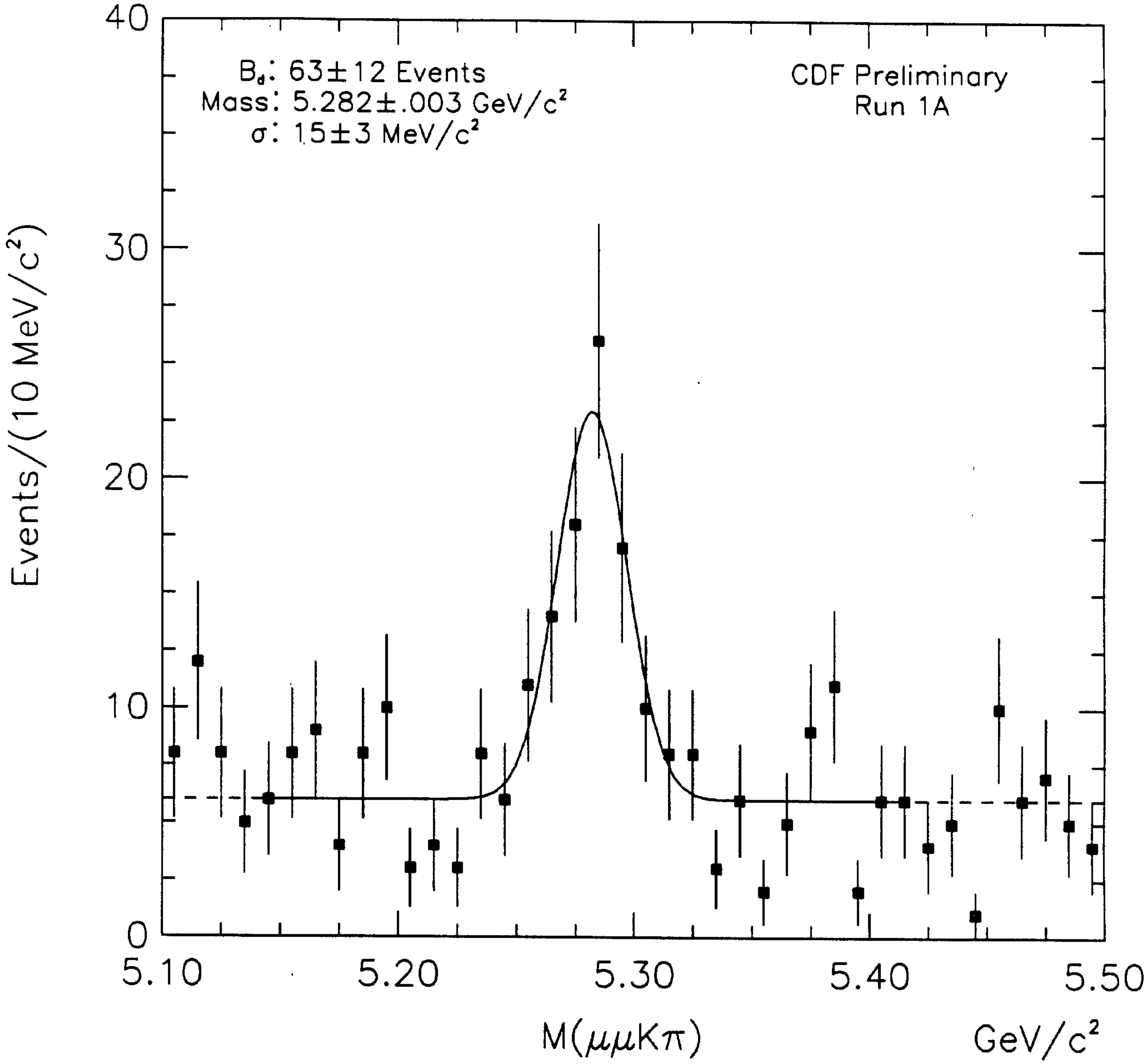

Figure 1: Invariant mass distribution for $B^0 \to J/\psi K^{*0}$. The curve is a binned likelihood fit to a gaussian plus a flat background.

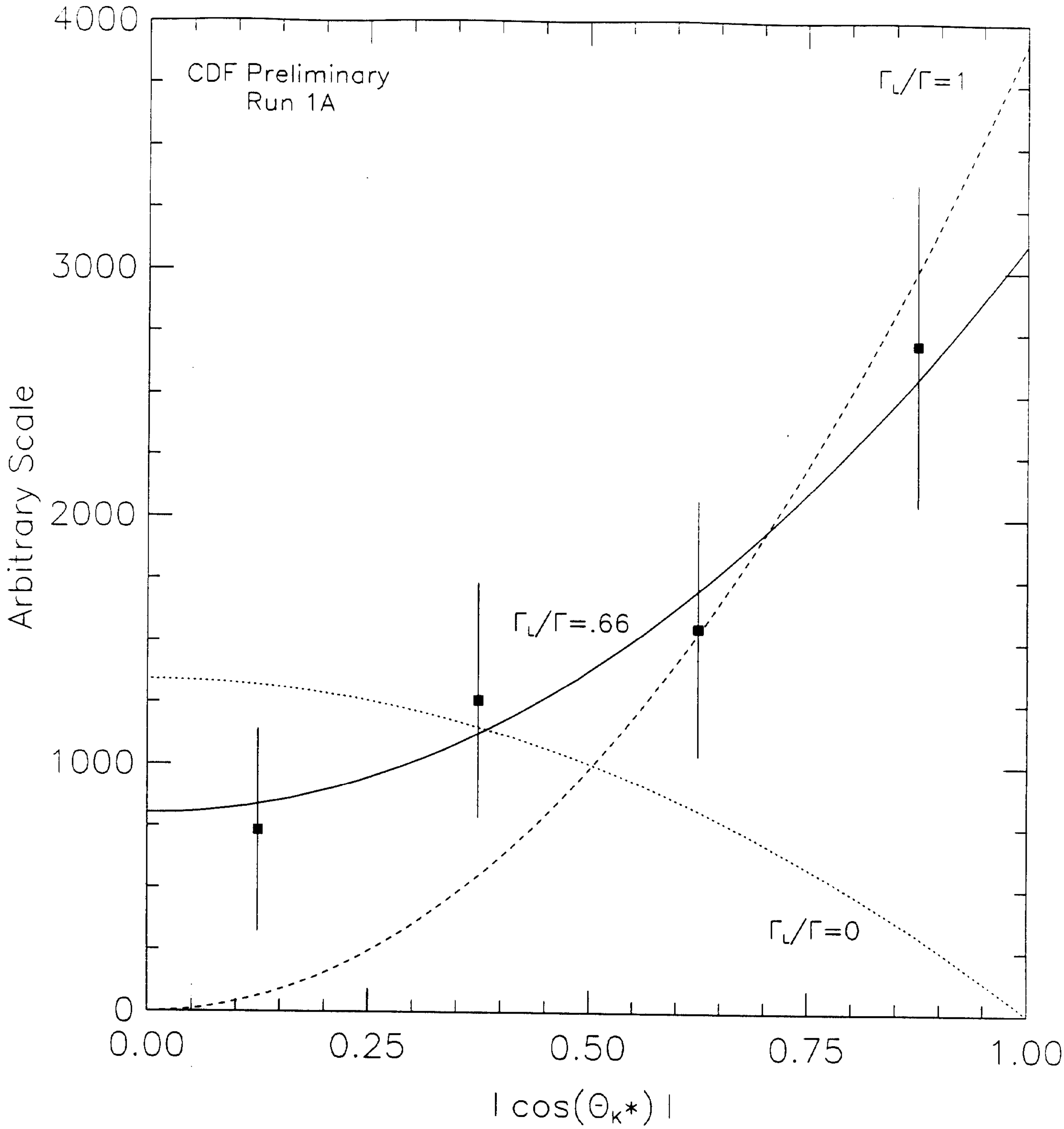

Figure 2: K^{*0} helicity angle distribution from the data, background subtracted and corrected for relative acceptance. The fit value of $\Gamma_L/\Gamma = 0.66$ is shown, plus the extremes.

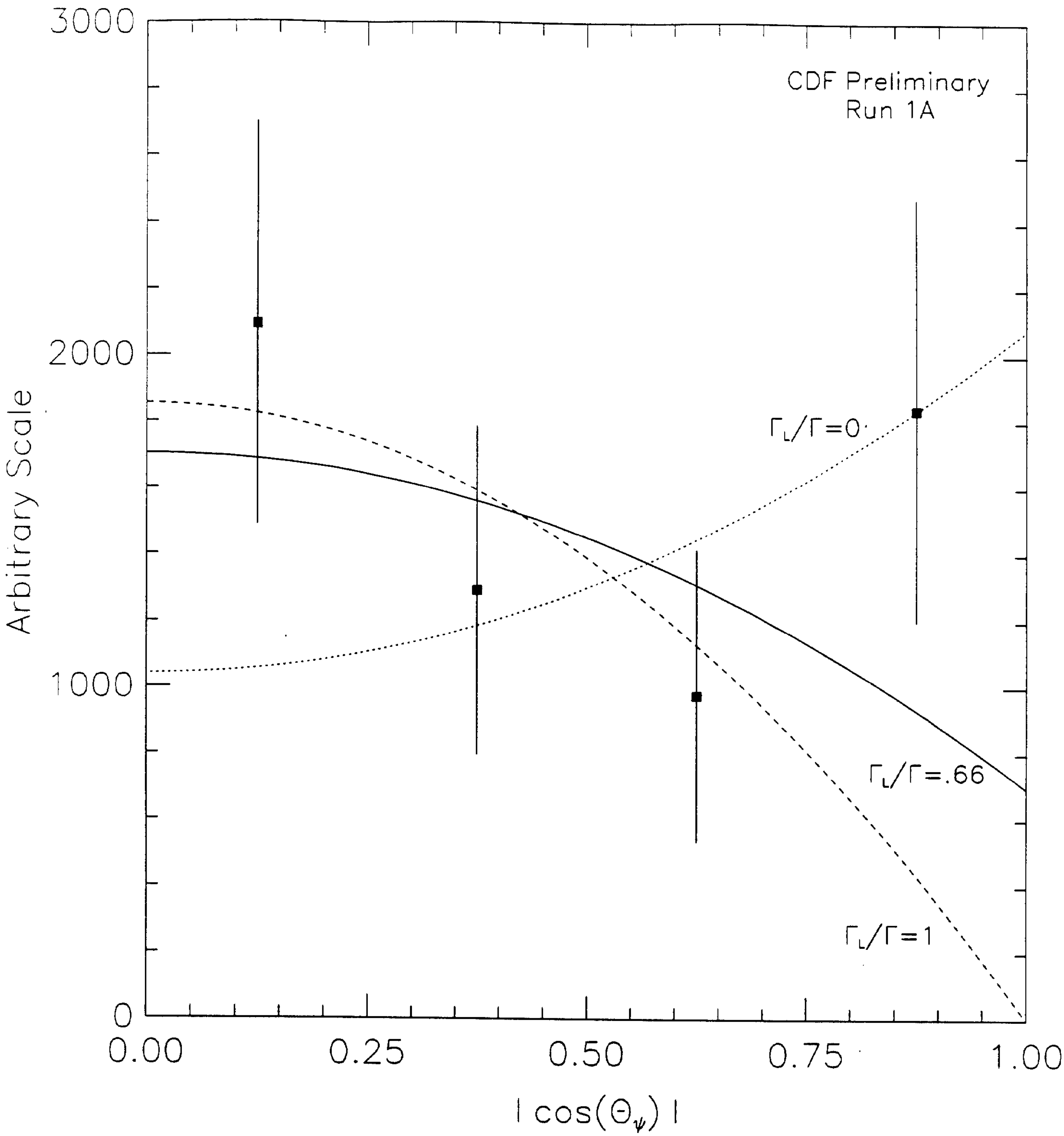

Figure 3: J/ψ **helicity angle distribution from the data, background subtracted and corrected for relative acceptance. The fit value of** $\Gamma_L/\Gamma = 0.66$ **is shown, plus the extremes.**